Climate Change Catastrophes

William A. Pizer

DISCUSSION PAPER

RESOURCES
FOR THE FUTURE

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Abstract

Most studies that compare price and quantity controls for greenhouse gas emissions under uncertainty find that price mechanisms perform substantially better. In these studies, the benefits from reducing emissions are proportional to the level of reductions, and such linear benefits strongly favor price policies (Weitzman 1974). Catastrophic damages, however, challenge that intuition as consequences become highly nonlinear. Catastrophe avoidance offers huge benefits, and incremental adjustments on either side of the associated threshold are relatively unimportant, suggesting a strong preference for quantity controls.

This paper shows that with catastrophic damages, both price and quantity mechanisms offer large gains over the business-as-usual alternative, and the difference between policies is never more than 10%. Catastrophe avoidance is much more important than efficient catastrophe avoidance. Although previous studies favoring price policies in the presence of uncertainty have worried that catastrophes would reverse their results, this analysis indicates that such concerns are not borne out.

Key Words: climate change, global warming, prices versus quantities, stock externalities, integrated assessment, uncertainty

JEL Classification Numbers: Q28, D81, C68

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1. Introduction

When uncertainty exists about control costs, alternative price- and quantity-based policies deliver qualitatively different responses when used to regulate an externality. In the case of climate change, many authors have argued, directly or indirectly, that price controls are more efficient.[1] In most cases, the argument is based on the idea that the damages from climate change are relatively "flat." That is, the additional damage from each additional ton of carbon emissions, each additional degree of warming—or whatever metric one chooses to measure climate change—is constant. Early work by Weitzman (1974), along with extensions by Newell and Pizer (1998) and Hoel and Karp (1998), show that price controls achieve much larger gains in expected welfare in this case.

Yet quantity-based regulation continues to pervade discussions and negotiations. There seems to be a gut instinct among those most concerned about climate change that the real threat is "catastrophic" damages—that is, the existence of some threshold for change that if surpassed will cause dramatically higher damage to the environment and society.[2] This contrasts sharply with most analytical studies, which fail to suggest a threshold.[3] Based on the price-quantity literature, however, such a threshold could explain a preference for quantity-based regulation.

This paper uses an integrated climate-economy model incorporating many sources of uncertainty to explore the differences between price and quantity controls when damages are potentially catastrophic. Surprisingly, we do not observe large *relative* improvements in welfare from using quantity controls over price mechanisms, even when catastrophic thresholds exist.

[1] Nordhaus (1994), Kolstad (1996), Pizer (1997), and Roughgarden and Schneider (1997)

[2] The best arguments revolve around sensitive climate processes, such as thermohaline circulation; see Broecker (1997).

[3] Manne (1996) and Yohe (1996) discuss the consequences of a single, low-probability, extreme event. Gjerde et al. (1997) show that if the Rio recommendations are optimal, it implies a 30% chance of catastrophe by 2090, where catastrophe is defined as a 75% loss of gross domestic product (GDP).

That is, the best-possible permit policy never improves the expected welfare obtained from the best-possible tax policy by more than 10%. In absolute terms, however, the improvement can be huge—on the order of hundreds of billions of dollars.

The explanation for this result is straightforward. In the textbook comparison of price and quantity controls under uncertainty, quantity controls directly manipulate production of the damage-causing substance; prices do not. If damages increase steeply at some threshold, quantity controls can be used to effectively avoid the threshold by strictly limiting production to some level below that threshold. Even the most aggressive price control fails to provide such a guarantee.

In reality, however, quantity controls may not precisely control the damage-causing substance. That is, quantity controls may be focused on a precursor. Strictly controlling carbon dioxide (CO_2) emissions, for example, does not strictly control atmospheric levels of greenhouse gases (GHG)—much of the accumulation process is poorly understood. Even less understood is the link between atmospheric gas levels and climate change. Therefore, if climate change (measured as temperature) is where the threshold is experienced—with anything above three degrees Celsius causing a catastrophe—quantity controls cannot offer the same guarantee they provided in the textbook example. Importantly, there are uncertain links that confound attempts to directly control climate change.

That said, it is less surprising that quantity controls fail to provide the silver bullet to deal with catastrophic damages. To be increasingly certain that climate change will not occur, we must set emissions limits low to guard against the risk that the climate turns out to be more sensitive than we initially supposed. This leads to overcontrol in most cases—just as with price mechanisms.

There is another reason why the relative gain under a quantity mechanism is never large. Catastrophic damages by their very nature imply that corrective measures will, on average, dramatically improve economic welfare. Even a price policy that proves less efficient than the optimal quantity control generates a huge welfare gain. Thus the *difference* between price and quantity controls, while large in absolute terms, is small compared with the expected policy gains themselves. This is exactly the reverse of the flat marginal benefit noncatastrophic result: Price controls generate welfare gains many times larger than even the optimal quantity control, but these gains are small in absolute terms.

The remainder of the paper spells out these results in greater detail. The next section describes the model and, in particular, the assumptions necessary to study catastrophic damages.

This section also reviews the basic theoretical results concerning the use price and quantity controls in the presence of uncertainty. Section 3 presents simulation results and discusses the range of consequences when we allow for catastrophic damages. This includes both climate change and damages, as well as optimal policy stringency, instrument choice, and welfare gains. The last section concludes.

2. An Integrated Climate-Economy Model with Uncertainty

2.1 Basic Description

The model used in this paper is a modified version of the DICE model developed by William Nordhaus (1994). Economic behavior involves a single sector of global economic activity. Global capital and labor are combined to produce a generic output each year, which is either consumed or invested in additional capital. A representative agent chooses the amount of consumption each period that maximizes her expected utility across time. Climate change enters the model through the emission of greenhouse gases arising in proportion to economic activity. These emissions accumulate in the atmosphere and lead to a higher global mean temperature. This higher temperature then causes damages by reducing output according to a damage function.

The opportunity to reduce the effect of climate change arises from the use of more expensive, GHG-reducing production technologies. In particular, there is a cost function describing the reduction in output required to reduce emissions by a given fraction. This cost function captures substitution both among and away from fossil fuels. Although the costs of reductions in any period are borne entirely in that period, the consequences of reduced emissions persist far into the future because of the longevity of greenhouse gases in the atmosphere.

A detailed description of both the behavioral equations and the quantification of uncertainty can be found in Pizer (1997). The main feature of this model is that uncertainty is captured by more than a thousand states of nature. There are 13 parameters that assume random rather than fixed values. Further, growth in the economy is assumed to experience small but permanent random shocks each year. The specification of uncertainty in this model was developed in Nordhaus and Popp (1997) and Pizer (1996).

2.2 Damages

Earlier simulations demonstrated that a quadratic damage function, as originally suggested by Nordhaus (1994), leads to a dramatic preference for price controls. Optimal price policies lead to nearly $350 billion in expected welfare gains, but optimal quantity controls yield only $70 billion.[4] The most common criticism, however, has been that these simulations ignore the possibility of *catastrophic* damages.

Although there are many interpretations of this comment, the simplest one is that the original specification ignores important uncertainty about the relationship between climate change, measured as warming, and damages, measured as loss of economic output. Uncertainty about the *level* of damages is included, but uncertainty about the *shape* of the damage function is not.

In particular, following Nordhaus's original specification, earlier simulations model the damage from climate change in the following form:

$$\left(\text{annual damage from climate change}\right) = \left(\frac{D_0\left(T/3\right)^{d_1}}{1 + D_0\left(T/3\right)^{d_1}}\right)\left(\text{output}\right) \quad (1)$$

where d_1 is always set to two, T is the temperature change relative to preindustrialization, and D_0 is a parameter describing the damages from three degrees of warming. Note that when $T = 0$, damages are zero, and when $T = 3$, damages roughly equal D_0. This form implies quadratic damages as a fraction of global output as long as $D_0\left(T/3\right)^2 < 0.10$, at which point the functional form begins to flatten the consequences.

The original analysis of uncertainty focused on the parameter D_0, allowing it to assume the values 0.0%, 0.4%, 1.3%, 1.6%, and 3.2%. This paper instead focuses on the exponent d_1.

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[4] Pizer (1997).

Table 1: Loss of Output Using Different Damage Parameters

	1.5° C	3.0° C.	6.0° C.
benchmark ($D_0 = 1.3\%$ and $d_1 = 2$)	0.3%	1.3%	4.9%
triple D_0	1.0%	3.8%	13.5%
triple d_1	0.0%	1.3%	45.4%

shows the difference between changing D_0 and changing d_1. The important difference is that while large values of D_0 generate large damages, they do not generate *precipitous* damages. In particular, a value of $d_1 = 2$ guarantees that the ratio between damages at six and three degrees of warming is roughly $2^2 = 4$. Meanwhile, a value of $d_1 = 6$ leads to a ratio closer to $2^6 = 64$ (where the curvature of the function $x/(1+x)$ for $x > 0.10$ flattens this effect).

This idea—that climate change can proceed without much consequence until warming reaches three degrees, followed by calamitous consequences with any further warming— captures our concept of catastrophic damage. Unfortunately, there is little empirical information concerning either the degree of steepness or the point at which the steepness begins. This lack of information is handled in two ways.

Knowing where the steepness begins—or the location of the "nonlinearity" or "kink," as we will call it—is, in fact, essential to finding cases where quantity controls will be preferred. If the location of the nonlinearity is unknown, we easily return to a case of potentially high but no longer steeply rising damages. Intuitively, if we are unable to locate the nonlinearity, we are unable to effectively set an appropriate quantity target to avoid it. Put another way, uncertainty about location *smears* the nonlinearity across a wide range of climate change.

We can visualize this effect by considering the following thought experiment. First consider the damage function (1)with $D_0 = 0.013$ and $d_1 = 6$. From flattens this effect).

we know that with six degrees of warming this leads to a 45% fall in gross domestic product (GDP). The same GDP loss at six degrees would occur using $D_0 = 0.200$ and $d_1 = 2$, but the implied loss at three degrees is much higher: 20% versus 1.3%. That is, using a quadratic damage function, we can replicate the *severity* of damages but not the *steepness*.

Now consider the effect of sticking with $D_0 = 0.013$ and $d_1 = 6$, but introducing a new source of uncertainty: the location of the kink. In particular, imagine a damage function of the form

$$\left(\text{annual damage from climate change}\right) = \left(\frac{D_0\left(\left(T-T_0\right)/3\right)^{d_1}}{1+D_0\left(\left(T-T_0\right)/3\right)^{d_1}}\right)\left(\text{output}\right)$$

where the notation is identical to (1) except that the random variable T_0 introduces a mean-zero disturbance to our knowledge of where the threshold for climate change lies. If we specify $T_0 \sim N(0,3)$, this suggests that the threshold for catastrophic damages might (with a 95% probability) lie anywhere between minus three and plus nine degrees of warming, relative to preindustrialization. That is, the threshold may be well beyond likely temperature changes in the next hundred years—or we may already be doomed. The effect of this uncertainty is to smear expected damages in a way that makes them appear quadratic. This effect is shown in Figure 1.

Figure 1: Expected GDP Loss Due to Global Warming

(alternative damage functions)
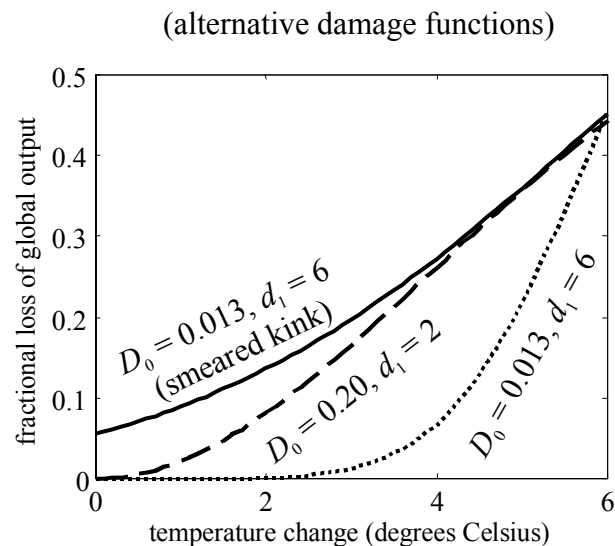
Since the effect of uncertainty about the location of a catastrophic threshold tends to smear the catastrophic consequences, we have chosen to ignore it in our simulations. We specify a nonlinearity at three degrees of warming and later test the sensitivity of our results to this particular value.

The second issue is the *degree of steepness*—in other words, appropriate values for d_1. Again, there is little empirical evidence as to how steep damages might in fact appear. We deal with this uncertainty by treating the parameter d_1, the catastrophic degree in some sense, as the focus of all our analysis. In particular, we explore how various results change as d_1 rises from a benchmark value of 2, up through extremely high values of 10–15. At these levels, 6 degrees of warming leads to a 99.8% loss of GDP.

2.3 Links between Emissions and Temperature Change

To explain the important results concerning the effectiveness of alternative policy instruments under the threat of catastrophic damages, it is important to recognize the basic links between emissions and temperature change. Emissions accumulate in the atmosphere, increase radiative forcing (solar energy absorbed by the atmosphere), and lead to warming. The DICE model and subsequent adaptations use a stylized model to capture these relationships and specify the uncertainties involved.

In the first step, emissions of carbon dioxide and other controllable greenhouse gases accumulate in the atmosphere according the following difference equation:[5]

$$M_t - 590 = \beta E_t + (1 - \delta_m)(M_{t-1} - 590)\,(2)$$

where M is the atmospheric concentration of carbon dioxide and E is net annual emissions (e.g., gross emissions minus abatement), both in billions of tons of carbon. The 590 term reflects the preindustrialization level of carbon dioxide to which, in the absence of anthropogenic emissions, the atmosphere would eventually return. The parameter $\delta = 0.00833$ reflects the rate at which atmospheric carbon dioxide is absorbed into the deep oceans, which are assumed to be an infinite sink. Finally, the parameter β, which assumes the values {0.50, 0.59, 0.64, 0.69, 0.78} with equal probability, indicates the rate at which emitted carbon dioxide is retained in the atmosphere. More sophisticated models of the atmosphere divide emissions into several "boxes," which then decay at different rates; here there are only two. Emissions either decay immediately or follow the relation in (2). Uncertainty remains, however, about how much of the emitted carbon dioxide remains in the atmosphere over long horizons, reflected in β.

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[5] The DICE model treats carbon dioxide (both energy and nonenergy sources) and chlorofluorocarbons (CFCs) as controllable. Henceforth, these are both referred to loosely as carbon dioxide (CO_2). See page 74 of Nordhaus (1994).

Given the amount of carbon dioxide in the atmosphere, it is still necessary to determine how that will affect important climate variables. In the DICE model, this is accomplished in two steps. The first is a link between atmospheric carbon dioxide and radiative forcing, a measure of how much energy is absorbed by the atmosphere. This is specified in the following logarithmic relationship:

$$F_t = 4.1 \times \log(M_t/590)/\log(2) + O_t$$

where F is the level of radiative forcing, in units of watts per meter squared, and O is the radiative forcings caused by *uncontrollable* greenhouse gases. This definition is such that every time the atmospheric level of carbon dioxide doubles from its preindustrialization baseline, forcings rise by 4.1 watts per meter squared.

Finally, we connect radiative forcings to our measure of climate change: temperature. Temperature evolves according to two difference equations:

$$T_t = T_{t-1} + (1/R_1)\left[F_t - \lambda T_{t-1} - (R_2/\tau_{12})(T_{t-1} - T_{t-1}^*)\right]$$
$$T_t^* = T_{t-1}^* + (1/R_2)(R_2/\tau_{12})(T_{t-1} - T_{t-1}^*)$$

where T is the surface temperature and T^* is the deep ocean temperature. The parameters R and τ determine how quickly the temperatures will equilibrate to a new level of forcings. The key parameter is λ, which measures the degree of temperature change necessary to balance a higher level of forcings. In particular, a doubling of carbon dioxide will eventually lead to a $4.1/\lambda$ rise in temperature; this is referred to as the *climate sensitivity*. In this paper, again following Nordhaus (1994), climate sensitivity takes on the values {1.46, 2.19, 2.93, 3.66, 4.39} with equal probability. That is, a doubling of atmospheric carbon dioxide could cause between 1.46 and 4.39 degrees of warming. This is range is consistent with discussions in the Intergovernmental Panel on Climate Change (IPCC 1990).

The main point of this brief discussion on the links between emissions and climate change is that this link is *uncertain*.[6] In particular, controlling emissions is not the same as controlling climate change. This fact will play an important role in explaining the relative merits of alternative price and quantity controls.

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[6] As recent work by Fischer et al. (1999) shows, uncertainty about this link may even be growing. This paper discusses whether warming has typically preceded increases in CO_2 concentrations, or vice versa.

2.4 Now versus the Future

A subtle problem with catastrophic damages is that the future—and in particular future *policy*—tends to dominate the analysis. In particular, we find the paradoxical result that the discounted benefits of policies to reduce emissions 50 or more years in the future may be considerably higher than the discounted benefits of policies to reduce emissions over the next 50 years, even when the benefits of this early policy are summed over hundreds of years.

In particular, one can easily imagine three future scenarios. In one, a brilliant technological breakthrough completely eliminates all emissions of carbon dioxide after 50 years. All we have to do, in this case, is watch the level of accumulated emissions in the near term and make sure it never pushes us past the catastrophic threshold. At the other extreme, one can imagine a future where geopolitics leads to dramatic increases in emissions, perhaps because developing countries refuse to meaningfully reduce emissions. In that case, we might consider reductions early on—to make sure we did not breach the threshold too early. However, toward the end of our 50-year horizon, it makes little sense to expend resources to reduce emissions if the world will blow past the threshold anyway. Under a middle scenario, considerable effort is again required to keep emissions under control in the future, but political institutions are developed in order to do so.

In all those examples, optimal behavior in the near future depends on events in the distant future (50 or more years). Welfare is also dominated by how the distant future plays out. To instead focus on the near term, we need to fix events in the distant future and compare alternatives in the near term. The most obvious course of action would be to fix behavior in the future at its optimal level. Unfortunately, optimal future behavior inevitably depends on choices today, making this approach inoperable. The approach we use is to fix future behavior in a way that presumes the problem of global warming is eventually "solved." In particular, we assume that 50 years after our policy begins, in 2060, emissions are costlessly reduced to a level of 6 GtC. One interpretation is that after 50 years, a new technology comes along that permits drastic emissions cuts at low cost. Another is that it simply becomes clear after 50 years that this is what

must be done. Either way, our analysis and results will be for policies over a 50-year horizon with the assumption that emissions are capped quite low after that point.[7]

2.5 Prices versus Quantities

Before we discuss the simulation results, it is important to understand the theory of instrument choice under uncertainty. In his seminal article, Weitzman (1974) lays out three basic ideas: (a) Uncertainty about costs from the social planner's or government's perspective leads to a different set of outcomes under price- and quantity-based controls in a regulated market. (b) Fixing the price leads to uncertainty in levels of output, whereas fixing the quantity leads to uncertain prices or marginal costs. (c) When the marginal benefit (demand) schedule is flat relative to the marginal cost schedule, the average deadweight loss is smaller under a price mechanism than under a quantity mechanism. In the extreme case where marginal benefits are constant and known, it is easy to imagine a price-based policy, set at the marginal benefit level, delivering the first-best, socially optimal outcome. Similarly, if marginal benefits are infinite at some output level (and presumably zero elsewhere), one can set a quantity-based policy to ensure that the particular output level is achieved—regardless of cost. Among intermediate cases, price and quantity controls fail to obtain the first-best, complete information outcome, and their performance relative to each other under incomplete information is governed by the relative slopes of the marginal costs and benefits.[8]

That result is particularly relevant for this paper. We begin with the observation that most analyses and conjectures about the relative efficiency of price and quantity controls for controlling greenhouse gases come to the same conclusion: Price controls dominate. The caveat to this conclusion, however, has been that presumably with sufficiently dramatic—and steep—

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[7] The "value" of this costless reduction in emissions is tremendous. Under the assumption of catastrophic damages, business-as-usual emissions lead to a 40% probability that the economy will be devastated (losing more than 50% of GDP) within 150 years. Capping emissions at 6 GtC in the year 2060—and doing nothing in the interim—reduces that probability to 5%. This generates an estimated welfare gain of around $100 *quadrillion*. This fanciful number, which pops out of the numerical analysis, is more than a thousand times the size of the global capital stock in 1995, representing the value of avoiding the nearly one-in-two chance that the world is destroyed in the next 200 years.

[8] Many extensions have been conducted on this basic result, including correlation of uncertainty in costs and benefits (Stavins 1996), combining price and quantity controls (Roberts and Spence 1976), and most recently, the extension to stock externalities (Newell and Pizer 1998). All of these extensions continue to support the basic premise that tendencies toward flatter marginal benefits favor price controls, and tendencies toward steeper marginal benefits favor quantity controls.

marginal damages, it would be reversed. This caveat is based on the intuition that if there is a threshold beyond which catastrophic damages occur, quantity controls should be the most efficient mechanism for preventing such a breach. We now discuss how and why this is result is not as robust as it appears.

3. Simulation Results

As a first cut at the question of how the potential for catastrophic damages affects policy choice, we compare two models. The first serves as a benchmark and specifies damages as a quadratic function of the change in temperature. The second makes the extreme assumption that damages are determined by the change in temperature (divided by three degrees Celsius) raised to the 12th power. This leads to negligible consequences as long as the temperature change remains below three degrees but annihilates the economy for anything more than four degrees.

### 3.1 Catastrophic versus Quadratic Damages

For both models we experiment with price- and quantity-based GHG policies—imposing carbon taxes or, alternatively, implementing a tradable permit system—and search for the stringency (tax rate or permit level) of those policies over time that maximizes expected social welfare. We assume that the future policy must be determined now and that it is not adjusted in the future.[9]

Under the benchmark assumptions of quadratic damages, we find that optimal price policies generate $138 billion in expected net benefits versus only $20 billion for the optimal quantity policy. This represents a difference of about $118 billion or, alternatively, a 590% improvement of prices over quantities. The optimal price policy begins at around $8/tC in 2010, rising to $30/tC by 2060. The optimal quantity control begins at 13GtC in 2010 and rises to nearly 34GtC by 2060. The left panel of Figure 2 shows the range of temperature changes in 2100 resulting from these two policies alongside the uncontrolled baseline. The effect of both policies on future temperature change is marginal, with the likelihood of a temperature rise

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[9] This raises two questions: (1) How rapidly will the underlying uncertainty be resolved? (2) How adjustable are policies once they are put into place? In this paper, we maintain that policies are chosen for next few decades and are not updated.

greater than four degrees falling from 9% in the baseline to only 8% and 6% under the optimal price and quantity controls, respectively.

Figure 2: Distribution of Temperature Change in 2105 under Optimal Price and Quantity Controls

quadratic damages   catastrophic damages
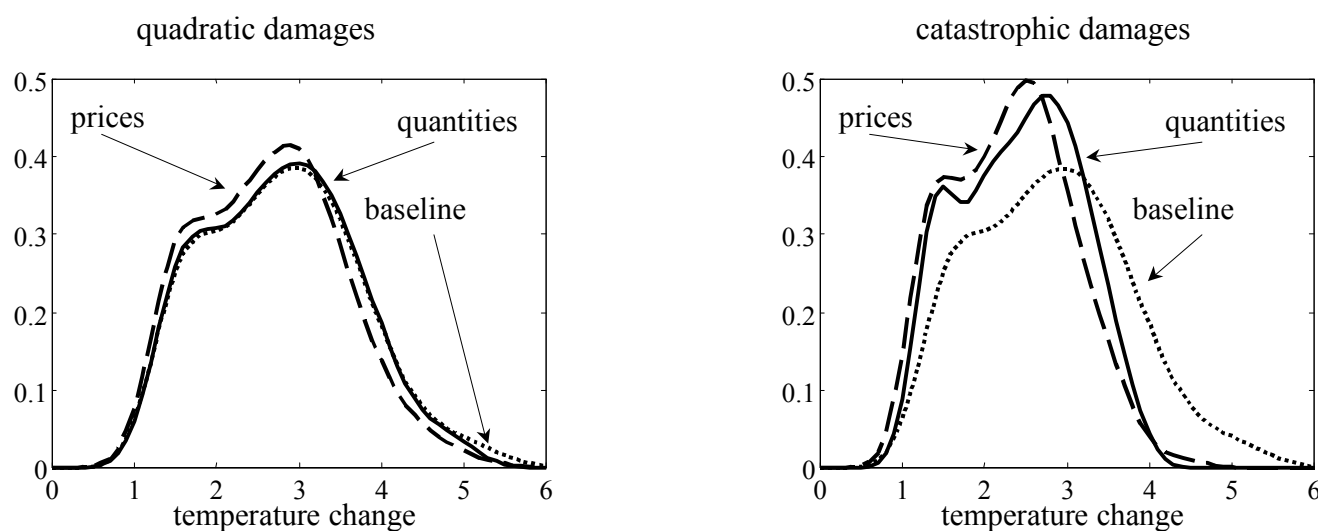

Introducing the potential for catastrophic damages dramatically changes these results. The observed temperature change in 2105 never rises above four degrees, as shown in the right panel of Figure 2 (there is a slight "tail," which arises from the smoothing algorithm). The avoided catastrophe now generates huge net benefits from both policies: The optimal price and quantity controls generate more than a $34 trillion gain in welfare.[10] If no measures are taken, the model forecasts that by 2100 there is an 5% chance the economy will be completely devastated, with damages exceeding 50% of output.[11] Therefore, the estimated gains reflect the value of avoiding this probabilistic catastrophe in the future.

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[10] This gain of $34 trillion represents nearly half the value of the global capital stock in 1995.

[11] As discussed in Section 2.4, emissions are costlessly reduced to 6 GtC after 2060 to obtain reasonable results in the face of catastrophic damages. Without this costless reduction, the chance of catastrophe is 18% by 2100 and 45% by 2200 in the absence of any policy.

To obtain the reductions in temperature change, far more aggressive policies are required. The optimal quantity policy with quadratic damages began with a 13 GtC emission limit in 2010, rising to more than 30 GtC over 50 years, but with catastrophic damages that limit is only 10 GtC in 2010 and falls to less than 8 GtC by 2060. Similarly, catastrophic damages lead to an optimal price policy that begins at \$35/tC in 2010 and exceeds \$500/tC by 2060. Figure 3 shows the optimal price and quantity policies for both quadratic and catastrophic damage functions.

Figure 3: Optimal Price and Quantity Policies
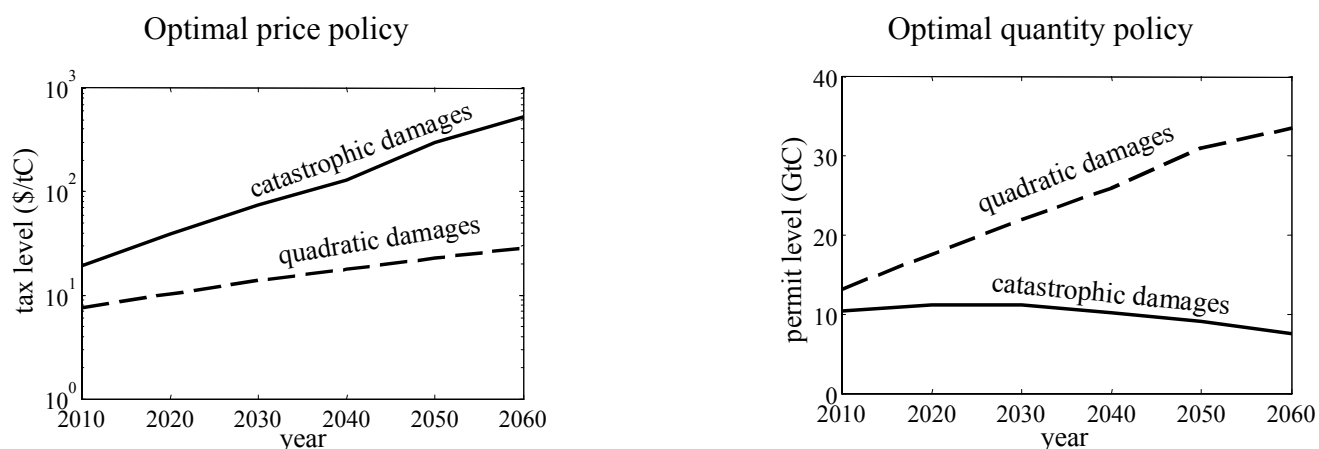
An interesting interpretation of the optimal quantity policy depicted in Figure 3 is in terms of revealed preference, or more precisely, "revealed belief." Since proponents of a strong climate change policy often talk in terms of using quantity-based controls to stabilize emissions, this analysis suggests the kinds of damage scenarios necessary to recommend such a policy. Although there is little evidence to suggest such sudden and dire consequences—and, if there were, to pinpoint the precise threshold—such assumptions are required in order to recommend such an aggressive policy stance. In particular, stabilizing quantity-based targets is optimal only when there is a well-defined threshold with clearly catastrophic consequences on the other side.[12]

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[12] This explanation for why someone might argue in favor of emissions stabilization focuses on damages as the crucial issue, assuming that everyone agrees with the remaining elements of the model. Critics might, for example, take issue with the efficacy of prices (that firms will optimally reduce emissions until price equals marginal cost) or with the use of historic rates of return on capital to discount future consumption.

3.2 Price versus Quantity

Comparing the relative merits of alternative price and quantity mechanisms, the optimal quantity-based policy generates more than $600 billion additional expected net benefits. Though large in absolute terms, this number represents barely 1% of the gains from either policy. One way to interpret this is to suggest that the overwhelming priority should be to get *some* policy in place, and to worry about the precise implementation later. This is in sharp contrast to the quadratic damage case. There, the difference between policies was a large fraction of the overall gain, suggesting that greater emphasis should be placed on choosing the right instrument if a policy is, in fact, implemented.

The preference for quantity-based policies follows the original Weitzman intuition developed earlier in the paper. As the marginal benefit schedule becomes increasingly steep, it will eventually tip the scales in favor of quantity-based policies. Recent extensions to Weitzman's work by Newell and Pizer (1998) offer additional intuition. Their results show that when dealing with stock externalities, quantity policies are preferred to price policies only when it is optimal to stabilize the stock level rapidly . Although the quadratic results fail to suggest any effort to stabilize the stock of CO_2, the optimal policies with catastrophic damages indicate an intentional stabilization by 2100.

Despite this consistency with economic theory, there are at least two important qualitative differences. The first is that almost all theoretical work on the price versus quantity issue has focused on linear marginal cost and benefit schedules. With catastrophic damages, both marginal costs and—in particular—benefits are highly *nonlinear*. This means that undercontrol is much worse than overcontrol, so the optimal price policy will necessarily skew toward overcontrol (e.g., higher than the expected marginal cost at the optimal quantity level). This should arguably work against price policies, which necessarily involve considerable overcontrol to avoid the devastating undercontrol outcomes.[13] Indeed, if we examine Figure 2 closely, we can see that the optimal price policy avoids the same high-temperature outcomes as the quantity policy in order to avoid catastrophic consequences. In the process, however, the entire distribution of temperature outcomes is shifted to the left, reflecting overcontrol in those states of nature where emissions are not particularly high.

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[13] See Yohe (1978).

Working in the opposite direction is the reality that quantity controls do not directly influence temperature change. As noted earlier, there are uncertain links between emissions and temperature change introduced by uncertainty about the fraction of carbon dioxide that persists in the atmosphere and the amount of warming caused by a change in atmospheric CO_2. Intuitively, this creates the same problem for quantity mechanisms that plagues price controls: the need to overcontrol in many cases to guarantee that the threshold is not breached in the extreme cases.

Specifically, we see that quantity controls leave the degree of temperature uncertain in the right panel of Figure 2. If temperature were in fact a direct control, we would expect to see a cutoff point, with no temperature changes above the cutoff and no effect on temperature change below. Instead, we see shifts toward lower temperatures throughout the distribution under the quantity policy, indicating overcontrol.[14]

3.3 Intermediate Cases

Although the quadratic versus catastrophic comparison shows the stark difference between assuming gradual rather than precipitous damages, it ignores the continuum that lies in between. We now consider varying the nonlinearity parameter d_1 over a range of values between 2 and 12. For each value, the optimal policies and consequences are be computed and compared. In particular, we consider how the degree of nonlinearity affects stringency as well as the choice between price and quantity controls.

Figure 4 shows the effect on stringency for both price and quantity policies. Figure 3 indicated that catastrophes introduced more significant impacts in the future, with larger differences between the quadratic and catastrophic cases occurring in 2060 than in 2010. However, Figure 4 makes this point much more concrete: Going from quadratic to cubic damages hardly affects policy in 2010, but in 2060 there is a 30% fall in the optimal permit level and a 30% rise in the optimal price level. We can also identify the point ($d_1 \approx 8$) where the optimal policy involves essentially flat emissions levels.

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[14] Yohe (1978) shows that when the quantity control does not, in fact, perfectly control the output level, the increased benefit uncertainty pushes the welfare measure toward price mechanisms.

**Figure 4: Effect of Nonlinear Damages on Optimal Price and
Quantity Levels in 2010 and 2060**

Optimal price instrument   Optimal quantity instrument
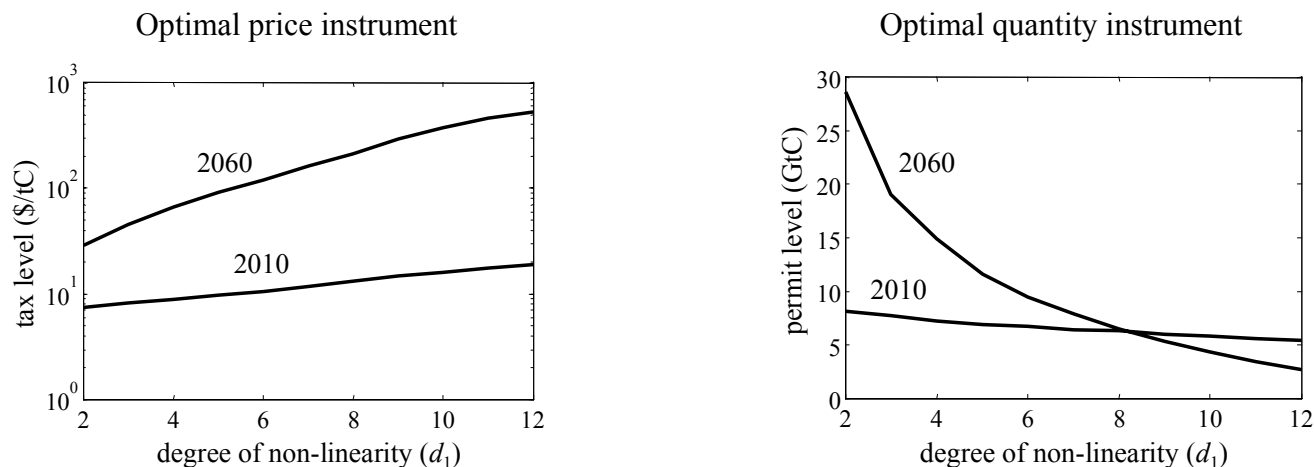
The implication of this result is surprising. Even with a known catastrophe occurring with more than three degrees of warming, the optimal emissions level in 2010 of 10 GtC is only 25% below the target with quadratic damages. This remains noticeably higher than the global 1990 emissions level of 8.5 GtC. The only way to support lower targets earlier to is to specify catastrophes at an even lower level (less than three degrees) of climate change. Discounting continues to make the delay of emissions reductions desirable.
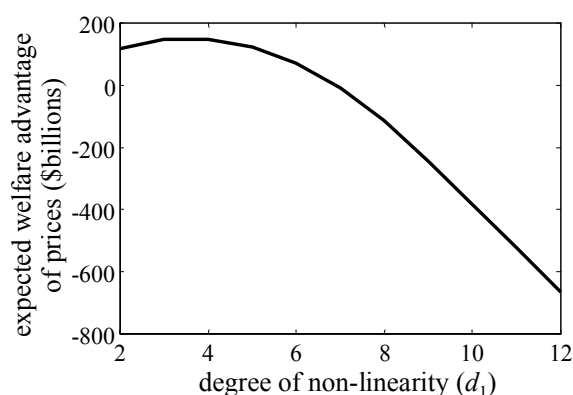
A second observation is that to maintain or lower the emissions level in the future, the marginal cost of control (e.g., permit price) will be dramatically higher. Under the quadratic assumptions, prices rise from \$7/tC to perhaps \$35/tC over 50 years and controlled emissions more than double. To avoid that doubling, as we find desirable when $d_1 \approx 8$, the price must rise to more than five times that amount—more than \$200/tC.

Since the original motivation for this work was to understand how the apparent efficiency of price mechanisms relative to quantity controls depends on the damage function, we now examine the relative advantage of price mechanisms as a function of the degree on nonlinearity in damages. Figure 5 shows the relative advantage of prices in both absolute terms and as a fractional improvement over quantity controls. The absolute difference is the more traditional measure (dating back to Weitzman's original definition of "Δ"), but the fractional improvement measure offers an important insight. Even though there may be a large absolute gain to using one instrument over another, a small fractional improvement suggests that the more important issue

is to remedy the problem. With a small fractional gain, one can also imagine that other features of the policy (e.g., handling of revenue, compliance) may involve larger gains than the choice of instrument. Finally, since the results of simulation models should be viewed as qualitative guides, emphasizing results that depend on absolute measures inherently stretches the model's credibility.

Figure 5: Effect of Nonlinear Damages on the Relative Advantage of Price Mechanisms

Relative advantage (absolute difference)   Relative advantage (% of quantity gain)
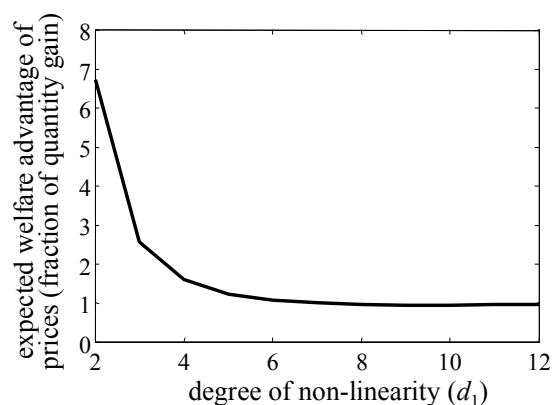
Several interesting patterns emerge in Figure 5. The first is that prices continue to be preferred until the nonlinearity becomes significant. The crossover occurs when $d_1 = 6$, at which point six degrees of warming leads to a nearly 50% loss of GDP—already a rather catastrophic scenario.

The dollar difference between price and quantity controls also exhibits a parabolic shape, starting with a zero difference when damages are independent of temperature change ($d_1 = 0$), reaching a maximum at $d_1 = 3$, declining to zero when $d_1 = 6$, then continuing to decrease at an ever larger rate. Although the pattern for $d_1 > 3$ follows Weitzman's basic intuition—that steeper benefits (damages) increasingly tilt the social welfare measure toward quantity controls—the pattern for $d_1 < 3$ apparently does not.

Unlike Weitzman's stylized model, we are not holding the output level constant as the marginal benefit schedule changes; nor is the marginal cost schedule linear. Instead, flatter marginal benefits imply lower levels of abatement. Note that we assume costs take the form

$$(\text{control costs}) = b_1 (\text{abatement}/\text{emissions})^{b_2} \times (\text{output})$$

where b_1 assumes a range of values between 2.7 and 13.3% and $b_2 = 2.887$.[15] Therefore, as the abatement level declines, so does the slope of marginal costs. Since the relative advantage (in absolute terms) of price over quantity controls depends on the relative slopes of marginal costs and benefits, this would appear to introduce ambiguity as to whether the relative advantage should decline or fall as benefits (i.e., damages) are varied from catastrophic to constant. However, since abatement/emissions can never exceed unity, there is a maximum on the marginal cost slope—eventually, quantity controls must be preferred for steep enough benefits/damages. Similarly, as the benefits become increasingly flat, we approach a situation where the optimal policy is to do nothing, and prices and quantities are equally effective in that regard. Therefore, at low values of d_1 the relative advantage must tend to zero.[16]

Examining the right panel of Figure 5, we see that quantity controls fail to dominate prices in a relative sense, but price controls clearly do. At low values of d_1, the fractional gain of prices over quantities is huge—and continuing to rise. This indicates that for modest policies, quantity controls are extremely inefficient. At high values of d_1, however, quantity controls fail to show a symmetric effect. That is, although price controls can generate many times the expected welfare gains of quantity controls for low values of d_1, quantity controls offer only modest (10%) improvements over prices at high values of d_1.

As noted earlier, there are two explanations. The first is that with high values of d_1, the gain is so large for both policies that any difference is necessarily small. Both policies "solve" the catastrophe problem, but prices imply considerable overcontrol in many cases.[17] The second is that quantity controls are not, in fact, perfectly controlling the cause of damage—namely, temperature change. Therefore, quantity controls must also overcontrol emissions to avoid the catastrophe risk, making them more similar to the price mechanism.

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[15] See Nordhaus (1993).

[16] Weitzman's (1974) expression has the difference in slopes multiplied by σ^2/c_2^2 where σ^2 is the variance of cost shocks and c_2^2 is the square of the marginal cost slope. This suggests that the relative advantage expression should, in fact, explode as $c_2 \to 0$ as the optimal abatement level declines to zero. In reality, the cost shocks are best thought of as shocks to the output level arising from uncertainty about the baseline. This eliminates the $1/c_2^2$ factor.

[17] This assumes that a price control can, in fact, be set strict enough to guarantee that the catastrophe never occurs. This might not be possible. In our simulations, however, one can make this guarantee, since only a finite number of states are used to approximate the limitless dimensions of uncertainty.

4. Conclusions

Earlier work found that under uncertainty, price mechanisms offered considerable efficiency gains over quantity-based controls for regulating greenhouse gas emissions. This was predicated on the assumption that damages arising from changes in the climate are a gradual phenomenon: Slightly more change means slightly more damage. Under these assumptions, it is hard to find any reason to support quantity controls. Rather than attempting to hit a fixed quantity target at any cost, we should instead price emissions at our best guess concerning their rate of marginal damage. Since there is a real risk that the costs of hitting a fixed quantity target can be extremely high—depending on growth and technology—such targets make little sense.

This remains true as long as the damage from climate change is a gradual phenomenon. By assuming that climate change damages rise dramatically at a particular threshold, intuition suggests that it will make sense to adopt the quantity-at-any-cost approach. This paper shows that to be the case: If we assume that catastrophic damages occur once global warming exceeds a specific threshold, we find that quantity controls are indeed desirable. We also find it optimal to hold emissions constant in spite of the increasing pressure from economic growth.

Despite the intuition and initial results, the argument for quantity controls in the face of catastrophic damages turns out to be rather shallow. In particular, the large gains from using quantity instead of price controls—nearly $650 billion—amount to no more than 10% of the gain from either optimal policy. This contrasts with the quadratic damage case, where the gains under price controls are nearly six times the gains under quantity controls. Although the large dollar difference indicates that the issue of instrument should not be ignored, the small relative difference suggests that other concerns could be equally important. Efficiency differences related to revenue handling, monitoring and enforcement, and so forth will likely be in proportion to the size of the gain. Such issues might therefore outweigh the efficiency gain of quantity controls. A small relative difference in welfare gains also suggests that it is more important to solve the problem by any means than to worry extensively about the instrument.

There are two explanations for the weak support for quantity controls. The first is that with catastrophic damages, the overwhelming concern becomes solving the problem. Doing so more or less efficiently becomes a side issue. This contrasts with the case of modest damages captured by quadratic damages. There, the total gains are much smaller, and choosing the right instrument is much more important—solving the problem with a quantity mechanism misses more than 80% of the gains possible with prices.

A second reason that quantity controls fail to provide a more significant relative improvement is that they do not precisely control the source of damages: temperature change. Since we are instead regulating emissions of carbon dioxide, we have to reduce emissions to the point that they fail to generate significant climate change even in the worst possible scenario (where temperature change is extremely sensitive to emissions). This leads to considerable overcontrol of emissions in many cases. But this is exactly the source of inefficiencies under a price mechanism: Using a price mechanism, catastrophic damages lead us to choose a price level that is high enough to avoid significant temperature change in all cases. This requires significant overcontrol of emissions in many of the uncertain outcomes.

When we examine the continuum of nonlinearities ranging from quadratic to catastrophic, we see that price controls continue to dominate quantity controls until the degree of nonlinearity is rather significant. At the point where they generate equal gains, damages would likely involve a 50% loss of GDP from six degrees of warming—already a rather catastrophic vision. Quantity controls become the preferred instrument only for more extreme catastrophic specification. The definition of catastrophic damages used in this analysis, where six degrees of warming annihilates the economy, not only generates a preference for quantity controls but also supports a policy of stabilizing emissions. This result suggests that from a revealed preference approach, support for an emissions stabilization policy, such as the Kyoto Protocol, requires an extremely pessimistic vision of climate damage.

The main conclusion is that price mechanisms are not a bad policy choice in any case. Although less beneficial than quantity controls under the extreme assumptions considered in this paper, they are never far behind in relative terms. Under less dramatic assumptions about the severity of damages—or when the threshold for severe damages is unknown—prices end up ahead. This paper also shows that damages have less of impact on the optimal stringency of policy in the short run. Therefore, rather than arguing over the appropriate target, policymakers should focus on choosing the correct instrument—namely, prices.

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